The visual and functional impacts of astigmatism and its clinical management

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Abstract

Purpose: To provide a comprehensive overview of research examining the impact of astigmatism on clinical and functional measures of vision, the short and longer term adaptations to astigmatism that occur in the visual system, and the currently available clinical options for the management of patients with astigmatism.

Recent findings: The presence of astigmatism can lead to substantial reductions in visual performance in a variety of clinical vision measures and functional visual tasks. Recent evidence demonstrates that astigmatic blur results in short-term adaptations in the visual system that appear to reduce the perceived impact of astigmatism on vision. In the longer term, uncorrected astigmatism in childhood can also significantly impact on visual development, resulting in amblyopia. Astigmatism is also associated with the development of spherical refractive errors. Although the clinical correction of small magnitudes of astigmatism is relatively straightforward, the precise, reliable correction of astigmatism (particularly high astigmatism) can be challenging. A wide variety of refractive corrections are now available for the patient with astigmatism, including spectacle, contact lens and surgical options.

Summary: Astigmatism is one of the most common refractive errors managed in clinical ophthalmic practice. The significant visual and functional impacts of astigmatism emphasise the importance of its reliable clinical management. With continued improvements in ocular measurement techniques and developments in a range of different refractive correction technologies, the future promises the potential for more precise and comprehensive correction options for astigmatic patients.

Introduction

Astigmatism is a refractive condition where parallel rays of light entering the eye are brought to a focus at two distinct focal lines perpendicular to each other, rather than to a single focal point. It occurs due to meridional variations in the curvature and/or refractive index and/or alignment of the eye's optical components along their principal meridians. Uncorrected astigmatism can result in substantial reductions in visual performance and may be associated with altered visual and refractive development. The first account of the correction of astigmatism was made by the astronomer Sir George Biddell Airy in 1827, who had a cylindrical lens made to correct the approximately 4 D magnitude oblique astigmatic refractive error of his own left eye.[1] Airy described this spectacle lens for the correction of his astigmatism as "*satisfying my wishes in every respect*". Over the two centuries since this initial report of astigmatism and its successful correction, the available methods for correcting astigmatism, and our understanding of the impact of this refractive error on the visual system has increased considerably. In this review paper, we provide an update on our previous review of the aetiology of astigmatism,[2] and extend this work by providing a comprehensive overview of the numerous currently available clinical options for the management of astigmatism, and discussion of research examining the visual and functional impacts of astigmatism and its correction.

Prevalence, Ocular Origins and Aetiology of Astigmatism

Small amounts of clinically measurable astigmatism occur very commonly, with around 60% or more of the adult population documented to have ≥ 0.25 D of ocular astigmatism.[3,4] Estimates of astigmatic prevalence in the population vary depending on the definition of astigmatism used, and the age and ethnicity of the population examined, although most studies indicate that low levels of astigmatism (≤ 0.50 D) occur commonly, while high astigmatism (> 3.00 D) is rare. A large number of studies have documented consistent changes in the prevalence of ocular astigmatism with age (Figure 1).[5-43] In infancy a relatively high prevalence of ocular astigmatism is typically reported, with the magnitude of astigmatism usually reducing over the first few years of life.[5,44-47] Astigmatism prevalence typically remains stable in adolescence and adulthood,[29,48-50] and increases in prevalence in older age.[4,40,48,49] The axis of astigmatism also shows consistent variations with age (Figure 2).[25,29,33,39,42-44,48,51-55] In childhood and early adulthood, astigmatism is predominantly with-

the-rule (WTR) in axis (i.e. negative cylinder axis close to horizontal),[29,48-50,54] whereas in older age a shift towards a predominance of against-the-rule (ATR) astigmatism (where the negative cylinder axis is close to the vertical) usually occurs.[4,40,48-50] Most studies show the prevalence of oblique astigmatism (i.e. negative cylinder axis between 30°- 60° or 120°-150°) is less than WTR or ATR and it appears to remain relatively stable with age.[29,44,48,51,29] Studies examining age-related changes in both ocular and corneal astigmatism indicate that the changes in ocular astigmatism with age occur primarily due to changes in the magnitude and axis of corneal astigmatism.[40,48-50]

Although ocular/refractive astigmatism can occur due to meridional variations in the optical properties of, or misalignments between or tilts in the eye's refractive components, the large refractive index difference between air and the anterior cornea means that refractive astigmatism most commonly originates from differences in the curvature of the anterior corneal surface along its two principal meridians.[40,48,49] The contribution of the eye's internal optical components (i.e. the posterior cornea and the crystalline lens) to the total astigmatism of the eye is generally relatively small. Internal (or residual) astigmatism is most commonly found to be ATR in axis and estimates of the average magnitude of internal astigmatism have ranged from 0.30 to 0.85 D.[13,25,40,48,56-62] In younger populations, the astigmatism from the internal optical components tends to balance the predominantly WTR anterior corneal astigmatism.[63,64] Although the majority of studies estimate internal astigmatism to be approximately 0.50 D and ATR in axis, the relative contribution of each of the eye's internal optical components to this astigmatism is not clear, since these studies derive measures of internal/residual astigmatism through subtracting anterior corneal astigmatism from the total ocular refractive astigmatism.

Developments in ocular imaging and measurement techniques, such as Scheimpflug imaging and optical coherence tomography (OCT), have provided an improved understanding of the topographical characteristics of the posterior cornea and the crystalline lens, which has contributed to our understanding of the origins of internal/residual astigmatism. Recent studies utilising rotating Scheimpflug instruments to measure anterior and posterior corneal curvature in relatively large clinical populations of subjects with a wide range of ages have estimated the astigmatism contributed by the posterior cornea to be approximately 0.30 D in magnitude (with individual measured values ranging from 0.01D to 1.10D, and approximately 9% of eyes exhibiting more than 0.50D posterior corneal astigmatism[65]) and ATR in axis (i.e. the steepest meridian of the posterior cornea oriented

close to the vertical).[65,66] These studies also demonstrate that the magnitude and axis of posterior corneal astigmatism appears to remain relatively stable as a function of age. Therefore in younger age groups where the anterior cornea usually exhibits WTR astigmatism, the posterior cornea will at least partially compensate for the anterior corneal astigmatism. However, in older age groups where anterior corneal astigmatism is predominantly ATR, astigmatism from the posterior cornea will effectively add to the anterior corneal astigmatism and increase the ocular astigmatism. These findings suggest that for the most accurate assessment of total corneal astigmatism, for applications such as intraocular lens (IOL) calculations, the individual contribution of the anterior and posterior cornea should be considered, rather than assuming a fixed correlation between the anterior and posterior corneal surfaces (which is the approach used by traditional keratometric measures of corneal astigmatism, that use a refractive index of n = 1.3375 or n = 1.332 instead of n = 1.376 to approximate the relative contribution of the posterior cornea). Figure 3 illustrates some examples of patterns of anterior and posterior corneal astigmatism.

The toricity of the anterior and posterior crystalline lens surfaces have been measured through the analysis of Purkinje images in both adult[67,68] and pediatric[69] populations. These studies suggest that the toricity of the posterior lens surface is greater than the anterior lens surface, and that the anterior lens contributes WTR astigmatism, and the posterior lens ATR. Optical modelling on data from young adult subjects, assuming a uniform lens refractive index, has estimated an average contribution of ~0.50 D ATR astigmatism from the total crystalline lens.[68] It should be noted that these estimates based upon Purkinje imaging typically involve determination of curvature along a small number of meridians (e.g. four), can be prone to accumulated experimental errors (due to the multiple ocular measures required to determine astigmatic power), and rely upon assumptions regarding the refractive index of the crystalline lens that may not reflect the exact optical properties of the in-vivo lens.[68] More recently, high speed anterior segment OCT imaging has been used to quantify the 3-dimensional structure of the crystalline lens including the topographical characteristics of its anterior and posterior surfaces.[70] This technique, which applies sophisticated methods to correct for image distortions due to both the instrument scanning architecture (so-called “fan” distortion) and refraction of the measurement beam by the ocular components, demonstrated accurate quantitative measures of the crystalline lens in a physical model eye (errors in measured lens surface radii of curvature were less than 3% after distortion correction).[70] In-vivo measures on 3 human subjects were also performed, demonstrating the topographical characteristics of the anterior and posterior lens surfaces and the 3-D thickness profile of the lens across a central 5 mm diameter with good precision. These

measures indicated a trend for the anterior lens surface to exhibit WTR astigmatism and the posterior lens surface ATR. A recent study also utilised OCT imaging of ex-vivo porcine crystalline lenses to determine their 3-D surface shape, thickness and gradient refractive index properties.[71] Optical modelling based upon these data indicated that the presence of the gradient refractive index tended to result in a decrease in the overall astigmatism for the majority of lenses examined.[71] The use of these advanced imaging techniques in future research to provide detailed 3-D surface topography and thickness information in larger populations of human eyes in-vivo, combined with improved understanding of the gradient index distribution of the crystalline lens (which can also be derived from these imaging methods), will enhance our knowledge of the magnitude and axis of astigmatism contributed by the crystalline lens.

Although astigmatism is commonly encountered and managed clinically, the exact mechanism underlying the development of naturally occurring astigmatism (i.e. astigmatism not associated with ocular disease or induced by surgery) is still not clear. Similar to other refractive errors, the cause of astigmatism is likely to be multi-factorial, with a range of potential factors involved. There is evidence for a significant genetic contribution to astigmatism, with twin studies suggesting approximately 60% heritability for astigmatic refractive errors.[72,73] A recent genome wide association study provided suggestive evidence for the VAX2 gene (a homeobox gene involved in the regulation of eye development, and in the control of retinoic acid metabolism) as a potential candidate gene involved in astigmatism development.[74] In two studies of Asian populations, the PDGFRA gene on chromosome 4q12 (a gene with roles in cellular growth and proliferation cascades) has been found to show a genome wide statistically significant association with corneal astigmatism[75] and corneal curvature.[76]

Environmental factors are also likely to play a role in the development of astigmatism.[2] Factors such as eyelid pressure, extraocular muscle forces, and nutrition have all been implicated as potentially being involved in astigmatism development. The increased prevalence of astigmatism in patients with genetic syndromes associated with altered eyelid morphology (e.g. Down syndrome,[77] Treacher-Collins Syndrome[78] and Spina Bifida[79]), the changes in astigmatism associated with eyelid abnormalities (e.g. ptosis,[80] capillary haemangioma[81] and chalazia[82]), and the fact that corneal astigmatism can be altered by changes in eyelid position[83,84] and gaze direction[85,86] all support a potential role for eyelid pressure influencing corneal shape and hence determining astigmatism. The finding of an

association between astigmatic axis and the angle of the palpebral fissure in normal adults[87] and in children with high levels of astigmatism[88] also adds weight to the potential role of the eyelids in the development of astigmatism. Studies reporting changes in astigmatism following extraocular muscle surgery[89,90] and the increased prevalence of astigmatism in patients with nystagmus[91] also support a potential role for forces from the extraocular muscles in the development of astigmatism. It has also been hypothesised that poor nutrition may influence corneal structure and/or biochemical properties and in turn result in astigmatism.[92] A report of increased prevalence of astigmatism in children with a history of malnutrition in infancy,[93] and recent studies reporting an association between WTR astigmatism and body mass index (BMI),[94,95] tend to support a potential relationship between nutrition and astigmatism.

A recent study of a large population of young adults (n = 67,899) in Israel with astigmatism has highlighted a number of potential environmental factors associated with WTR astigmatism, including a longer perinatal photoperiod (i.e. those born in summer months with longer photoperiods exhibited a higher prevalence of WTR astigmatism), higher body mass index, and a lower intelligence score.[95] The authors also found that associations between these environmental factors and ATR and oblique astigmatism did not necessarily follow the same trends as those observed for WTR astigmatism which underscores the complexity of unravelling the various environmental factors associated with astigmatism. Although there have been a range of associations between certain ocular and environmental factors and astigmatic refractive errors that support environmental influences potentially determining astigmatism, the causative nature and relative importance of each of these factors remains to be determined by future research.

Visual and Functional Impact of Astigmatism

The significant visual and functional impact of uncorrected astigmatism underscores its clinical importance, and emphasises the need for its correction. The following section will discuss both the short term visual and functional effects of astigmatism and the longer term impacts of astigmatism on visual development.

Visual impact of astigmatism

It is well established that astigmatic refractive errors result in reductions in visual performance for both distance and near tasks. The optical effect of astigmatism upon retinal image quality can be modelled and/or demonstrated relatively easily. Astigmatism results in meridional variations in retinal image blur which is greatest along the axis of astigmatism (e.g. for WTR astigmatism the features oriented horizontally in the image are most blurred) (Figure 4). However, the exact influence of astigmatism upon visual function will also be dependent upon a range of factors such as the specific type of visual task being performed, the interaction with the subject's other ocular aberrations (i.e. the spherical refractive state of the eye and higher-order aberrations), pupil size, the accommodative state of the eye, the level of neural adaptation to astigmatism and the individual's subjective perception of blur.

A number of studies have investigated the influence of astigmatic blur upon visual function. These studies indicate that even relatively low amounts of astigmatism can lead to reductions in visual performance. Guo and Atchison[96] reported that on average 0.28 ± 0.12 D of induced cylindrical power was required for subjects to notice a reduction in clarity of a 0.1 logMAR line of letters. Not unexpectedly, studies examining the influence of astigmatism on distance visual acuity report that higher magnitudes of astigmatism typically result in greater decrements in visual performance.[97-104] Most studies have reported approximately linear declines in distance visual acuity with increasing imposed cylinder power, with approximately 1-2 lines of logMAR distance visual acuity reduction typically observed per dioptre of induced cylinder, depending upon the population examined and conditions of the measurements (e.g. age of subjects, pupil size, presence of active accommodation, correction of higher-order aberrations and the axis orientation).[99-102,104] Although most studies have examined high contrast visual acuity, similar magnitude decrements in acuity with induced astigmatism are also found for low contrast distance visual acuity.[100,104] Near visual acuity is also reduced by uncorrected astigmatism by a similar amount as distance visual acuity.[101,102] Other measures of visual performance such as contrast sensitivity have also been shown to be reduced with astigmatic blur and these effects have a strong orientation dependence, such as contrast sensitivity testing with gratings.[97,105] Measures of stereoacuity are also reduced by monocular and binocular induced astigmatism, with the most pronounced effects found for induced binocular orthogonal oblique astigmatism (i.e. axis 45° in one eye and axis 135° in the fellow eye).[106]

The impact of astigmatic blur upon vision appears to depend upon the axis of the induced astigmatic error. The reduction in distance visual acuity with induced astigmatism has been reported to be least with induced WTR astigmatism[97,98,100,101,103] and greatest with either ATR[97,98] and/or oblique astigmatism.[98,100,102,103] However, other studies have not found a strong effect of induced cylinder axis on the changes in distance visual acuity with astigmatism.[99,107] Some of the differences observed between studies may relate to the specific methodology used including the type of acuity chart (e.g. spatial frequency content and the orientation of critical details), the control of accommodation and pupil size, and the magnitude of astigmatism induced. It is likely that particularly for relatively low levels of astigmatism interactions with the eye's higher-order aberrations will also impact upon the visual effects of astigmatism. This is supported by the work of Atchison and Mathur[100] who induced low levels of astigmatism in their subjects, and noted substantial between subject variations in the influence of astigmatism of different axes on their visual acuity measures. The potential for the presence of higher-order aberrations to influence the visual impact of astigmatism was confirmed by De Gracia et al[108] who demonstrated that combining small levels of astigmatism (0.50 D) with higher-order aberrations (specifically the third-order aberration coma) can result in significant improvements in visual performance in some patients.

Recent studies have also explored the short term adaptation occurring in the visual system as a result of exposure to astigmatic blur.[109-113] These studies have examined whether a period of exposure to astigmatic blur results in changes in the perceived clarity of the retinal image. Sawides et al[109] demonstrated that a 2 minute period of adaptation to astigmatic blur significantly altered the perception of clarity in subsequently viewed clear images. These adaptation effects were dependent upon both the magnitude (with larger magnitudes of astigmatic blur resulting in larger adaptation effects over the range of blur examined) and axis of the astigmatic blur (e.g. adaptation to astigmatic blur in the vertical meridian caused subsequently viewed clear images to appear more blurred horizontally). These visual adaptations to astigmatic blur (at least in the case of vertical and horizontal astigmatic blur) have also been demonstrated to exhibit transfer between the two eyes (i.e. adaptation to astigmatic blur in one eye effects the subsequent perception of the clarity of images viewed by the fellow eye at the same meridian).[112] These short term visual adaptations appear to function to reduce the apparent visual impact of astigmatic blur, presumably to assist in adjusting to changes occurring in the visual environment and maintaining visual continuity despite changes in the focus of the retinal image. Ohlendorf et al[110] demonstrated that these visual adaptations result in an improvement in visual performance, by showing that a 10

minute period of adaptation to 3 D of uncorrected astigmatism resulted in approximately one line of improvement in visual acuity through the same astigmatic blur.

These short term adaptations to astigmatic blur also appear to be influenced by the subject's natural level of astigmatism, suggesting the presence of a longer term adaptation to a subject's habitual astigmatic refractive error.[111,113] Vinas et al[113] showed that the visual effects of astigmatic blur were greater in non-astigmats compared to astigmats, and furthermore that for astigmatic subjects, the degradation in visual acuity induced by astigmatic blur was least when induced at the same axis as the subjects' natural astigmatism, and greatest when induced perpendicular to this axis. Although the exact mechanism underlying the visual adaptation to astigmatism is not known, the relatively rapid time course (within only 2 minutes), the documented transfer of adaptation between eyes and the orientation selectivity all suggest a cortical origin of these adaptations to astigmatic blur.

In summary, astigmatism, even of relatively small amounts, results in reductions in visual performance, and these changes appear to be dependent upon both the magnitude and axis of astigmatism. The visual system also exhibits evidence of adaptation to astigmatism in the short term, which can lead to improvements in visual performance in the presence of astigmatic blur over time. These short term adaptations appear to be influenced by the subject's habitual levels of astigmatism, suggesting an interaction between short term and longer term adaptations in the visual system.

Functional impact of astigmatism

Given the documented effects of uncorrected astigmatism upon clinical measures of distance and near vision, it follows that astigmatism may also have substantial functional visual impacts, that could influence the ability to perform everyday tasks such as reading, computer work and driving. Astigmatism has been shown to significantly reduce functional near vision measures. In young adults, even relatively small levels (1.00 D) of induced astigmatism were shown to reduce reading performance, particularly for induced ATR astigmatism and small print sizes.[114] Induced astigmatism has also been reported to reduce reading speeds in presbyopes[101] and in pre-presbyopes under cycloplegia.[115] A significant reduction in task performance of a computer based editing task (increased task completion

time and number of errors) was also found to occur with 1.50 D of induced astigmatism.[116] These findings indicate that uncorrected astigmatism has the potential to impact a number of different common occupational visual tasks, particularly tasks with a high acuity demand.

Wolffsohn et al[101] examined the influence of induced astigmatism on the performance of a range of driving tasks (using a computer driving simulator), and despite astigmatism leading to significant reductions in both distance and near visual acuity, driving simulator task performance was not significantly affected by imposed astigmatic refractive errors up to 4.00 DC. However, it should be noted that relatively small magnitudes of spherical blur have been reported to result in a reduction in aspects of night-time on-road driving performance,[117] such as pedestrian recognition in normal young adults, which suggests that astigmatic blur could also potentially detrimentally influence on-road driving performance, particularly in sub-optimum viewing conditions (e.g. night-time, rain, the presence of oncoming headlights). Additional research examining the effects of various levels of astigmatic blur on real-world driving performance in a variety of viewing conditions is required to better understand the functional effects of astigmatism on driving.

There has been a long held anecdotal belief that uncorrected astigmatism can result in headaches and related asthenopic symptoms. In a study of 310 children with headache of unknown origin and 843 controls, Akinci et al[118] found a higher prevalence of astigmatism in the group with headache, whereas spherical refractive errors were not significantly different between groups. Hendricks et al,[119] in a study of 487 children also found a weak but significant association between headache and habitual (i.e. uncorrected) astigmatic refractive error, but only in boys. In contrast to these findings, Gil-Gouveia and Martins[120] compared a population of subjects with uncorrected refractive errors (including astigmatism) with a control group of subjects with optimally corrected refractive error and no refractive error, and found no significant difference in headache frequency between the groups, and no significant association between astigmatism and headache (although 72% of patients with headache and refractive error reported an improvement in headache frequency following correction of their refractive error). It appears further systematic, well designed research is required to more clearly understand the relationship between astigmatic refractive error and the occurrence of headache, particularly given the common occurrence of and broad multifactorial aetiology underlying headache symptoms.[121]

There is also some experimental evidence to support an association between asthenopic symptoms occurring following specific visual tasks, and even relatively small amounts of uncorrected astigmatism.[122,123] Wiggins and Daum[122] reported an increase in reported symptoms of visual discomfort in subjects with 0.50 D ATR induced astigmatism following a 25 minute computer reading task. More recently, a 10 minute computer reading task performed with 2.00 D induced oblique astigmatic blur resulted in a significant increase in reported eye and vision related symptoms (such as 'tired eyes', 'discomfort in eyes', and 'blurred vision') compared to performing the task with the optimal refractive correction.[123] Although a definitive, causative link between headache/asthenopia and astigmatism remains to be established, the current evidence does appear to support a potential contribution of uncorrected astigmatism to asthenopic symptoms.

Impact of Astigmatism on Visual Development

Significant uncorrected astigmatism present during childhood, particularly throughout the plastic period of ocular development (from infancy up to approximately school age[124]), has the potential to affect normal visual development and lead to amblyopia. In addition, childhood astigmatism has also been associated with abnormal binocular vision (i.e. strabismus) and with the development of myopia.

Similar to spherical refractive errors, astigmatic refractive errors are documented to undergo emmetropisation (i.e. astigmatism undergoes a significant reduction in magnitude) during childhood.[44,45] Children with astigmatic refractive errors that fail to emmetropise (i.e. do not reduce during infancy) are more likely to develop amblyopia. Abrahamsson and Sjostrand[125] observed that the presence of oblique astigmatism or increasing levels of astigmatism during childhood significantly increased the likelihood of developing amblyopia. Additionally, in a longitudinal study of children during the first two years of life, Ehrlich et al[47] reported that WTR astigmatism showed a greater reduction in magnitude (emmetropisation) compared to ATR astigmatism. More recent studies[126,127] investigating total ocular aberrations in children have reported that the magnitude of astigmatism is significantly higher in amblyopes (~1.25 to 2.00 D) compared to non-amblyopic, emmetropic control groups (~0.25 D). In addition, refractory amblyopes (i.e. amblyopes with best corrected visual acuity of 0.2 logMAR or worse following one year of conventional amblyopia therapy) typically display greater levels of astigmatism (>1.75 D) compared to successfully treated non-strabismic amblyopes (1.00-1.25 D) with similar spherical refractive errors.

Astigmatism that persists during early visual development results in a form of meridian specific visual deprivation whereby stimuli of certain orientations appear more blurred than others, despite optimal refractive correction (i.e. meridional amblyopia). Early evidence from animal models[128-130] and studies of humans[131-136] suggests that meridional amblyopia is a result of alterations in the visual cortex following abnormal visual experience (uncorrected high astigmatism) during childhood. The visual effects of meridional amblyopia may manifest as a reduction in grating acuity,[131,133] Vernier acuity[133] and contrast sensitivity[131,135,136] (dependent upon the orientation of the presented stimuli), while potentially in the presence of relatively normal levels of standard letter acuity, depending upon the type of astigmatism (mixed, myopic or hyperopic astigmatism).[137] The magnitude of these meridional differences in visual performance is proportional to the magnitude of the astigmatism.

In summary, there is a high prevalence of astigmatism during infancy which undergoes emmetropisation during the first few years of life. Persistent astigmatism beyond 2 years of age typically results in meridional amblyopia (more so for oblique or ATR orientations). Higher levels of astigmatism during youth are associated with poorer visual outcomes following spectacle correction and amblyopia therapy.

Astigmatism and strabismus

While the magnitude of astigmatism typically diminishes during infancy, astigmatic refractive errors may develop or increase in magnitude throughout childhood (in association with the onset or progression of myopia) and potentially trigger the development of strabismus due to a disruption of fusion, particularly if the astigmatism is unilateral. Abrahamsson et al[138] reported a high prevalence of astigmatism (≥ 1.00 D) in children with strabismus (30% at initial examination), however, longitudinal changes in refraction were largely due to an increase in hyperopia or anisometropia with little change in astigmatism. In a cohort of slightly older children up to 6 years of age, McNeer[139] noted that the development of astigmatism may result in a recurrence or deterioration of strabismus following surgical correction. While simulated uncorrected monocular astigmatism in healthy young adults does not appear to have a significant influence upon measures of horizontal near fixation disparity (up to 1.25 D),[140] children may have less fusional control compared to adults which could lead to a break down in binocularity with astigmatic blur, manifesting as a strabismus.

In a population of 6 year olds, Huynh et al[141] found no association between aniso-astigmatism and strabismus after controlling for refractive error and amblyopia. However, in a recent comprehensive study of childhood eye disease involving around 10,000 children, Cotter et al[142] reported that both astigmatism and aniso-astigmatism were independently associated with exotropia. Bilateral astigmatism of ≥ 2.50 D was the greatest risk factor (odds ratio = 5.88) and J0 aniso-astigmatism (i.e. an interocular difference in power vector J0 of ≥ 0.50 D, which indicates a between eye difference in astigmatism along the horizontal or vertical meridian) was also a significant risk factor for exotropia (odds ratio = 2.63) in children up to 6 years old.

Astigmatism in amblyopic eyes

A limited number of studies have investigated the corneal shape characteristics of paediatric amblyopic eyes (aged 5-10 years). Cass and Tromans[143] compared anisometropic and strabismic amblyopes to paediatric and adult controls and found no significant differences in corneal curvature between the fellow eyes, or between the different cohorts. Similarly, Wang and Taranath[144] used Scheimpflug imaging to examine hyperopic anisometropes with amblyopia and found no significant differences in mean anterior or posterior corneal curvature between the fellow eyes (~0.12 D steeper in the amblyopic eye). Conversely, Debert et al[145] observed that hyperopic esotropes displayed a flatter mean corneal curvature in the amblyopic eye (0.17 D), but no significant difference in the magnitude of astigmatism.

In a slightly older cohort of myopic and hyperopic non-strabismic paediatric amblyopes (7-8 years), Patel et al[146] observed that amblyopic eyes always displayed a greater amount of corneal (1.59 ± 0.94 D) and total astigmatism (1.10 ± 1.55 D) compared to the fellow non-amblyopic eye (corneal 0.88 ± 0.49 D and total 0.27 ± 0.44 D), but this difference was not statistically significant. In an adult population of non-strabismic anisometropes (mean age 38 years), significantly higher levels of corneal (2.00 ± 1.51 D) and total astigmatism (2.47 ± 1.95 D) were reported in the amblyopic eye compared to the fellow eye (corneal 1.17 ± 1.01 D and total 1.20 ± 1.08 D).[147] Bilateral amblyopes were also compared to a control group, and while corneal astigmatism was similar between cohorts, total astigmatism was significantly greater in the bilateral amblyopes (approximately double; 2.25 D compared to 1.21 D), suggesting that internal astigmatism is significantly greater in (bilateral) amblyopia. The calculated crystalline lens power in anisometropic and strabismic children also shows a significantly greater lens power in the amblyopic eye.[143] Changes in the crystalline lens

during the visual development of amblyopic eyes could potentially result in an increase in internal astigmatism due to asymmetries in the lenticular surfaces.

Structural abnormalities of the optic nerve head are also associated with astigmatism. Eyes with abnormal disc shape (e.g. tilted disc syndrome) typically display high levels of corneal and internal astigmatism with the axis of astigmatism corresponding to the longest disc diameter (direction of tilt).[148,149] This suggests that genetic factors contributing to optic nerve head morphology may also influence the magnitude and orientation of astigmatism. Lempert and Porter[150] also observed that the majority of amblyopic eyes display abnormal optic nerve head morphology compared to fellow non-amblyopic eyes. However, if this structural relationship between optic nerve head, crystalline lens and cornea was typical in amblyopic eyes, one would expect to see a significant asymmetry in corneal astigmatism between the fellow eyes of paediatric amblyopes, which is not the case.

In summary, corneal astigmatism appears to be similar between the fellow eyes of amblyopes during youth, but in older age groups there appears to be greater levels of corneal and total astigmatism in amblyopic eyes compared to fellow non-amblyopic eyes. Bilateral amblyopes display greater levels of internal ocular astigmatism compared to non-amblyopes, suggesting that the crystalline lens may be substantially altered in amblyopic eyes (in addition to a reduced axial length[143,146])

Astigmatism and spherical refractive error

It has long been hypothesised that the presence of astigmatism may influence the development of spherical refractive errors such as myopia.[151] While the presence of astigmatism in childhood could potentially aid in the regulation of the normal growth of the eye towards emmetropia (since astigmatism provides cues to the sign of defocus of the retinal image,[152] which could be used to guide the growth of the developing eye), it is also possible that degradation of retinal image quality as a result of astigmatism could disrupt the normal emmetropization process, and lead to the development and progression of myopia.[153]

A number of studies have reported an association between astigmatism (and greater magnitudes of astigmatism) and a higher degree of spherical myopic refractive error.[153-156] Some longitudinal studies of children have also reported a significant relationship between astigmatism and the prevalence and progression of myopia.[153,154] Fulton et al[154] observed that children with astigmatism ≥ 1.00 D (particularly oblique astigmatism) had higher spherical myopia and also displayed a greater amount of myopia progression compared to non-astigmatic children. Gwiazda et al[153] also followed a cohort of children and observed that infantile ATR astigmatism was associated with increased myopia and astigmatism during childhood (school age) which supports the hypothesis that uncorrected astigmatic errors may disrupt the emmetropisation process and influence myopia development. However, other studies of children have not observed an association between the magnitude of astigmatism and myopia progression.[157,158]

There is also some evidence from the study of anisometropia which suggests an association between astigmatism and spherical myopic refractive error (i.e. a greater magnitude of astigmatism in the more myopic of the two eyes)[159,160] or an increase in childhood spherical anisometropia associated with the development of astigmatism.[161] Recent large scale studies (up to 90,000 subjects)[162,163] also report a significant independent association between the magnitude of astigmatism and anisometropia, irrespective of the magnitude of spherical refractive error.

The axis of astigmatism also appears to be related to the magnitude of refractive error. Farbrother et al[155] observed that higher levels of both myopia and hyperopia (and higher levels of astigmatism) were typically associated with WTR astigmatism, while refractive errors closer to emmetropia were more often ATR in nature. In a cohort of severely myopic patients, Heidary et al[156] also observed a high prevalence of WTR astigmatism and a significant correlation between the severity of myopia and the magnitude of astigmatism. However, the magnitude and prevalence of astigmatism also varies with ethnicity,[24,51,54,59] which was not specifically controlled for in these studies.

While there appears to be a positive correlation between the magnitude of astigmatism and the degree of spherical ametropia (in particular, WTR astigmatism and myopia), it remains unknown if uncorrected astigmatism is a causative stimulus that promotes axial elongation

and myopia development or whether the association between astigmatism and myopia is simply a consequence of anomalous eye growth.

The Clinical Correction of Astigmatism

The preceding sections have outlined the known effects of astigmatic refractive errors on vision, functional vision and visual development. These short term and longer term effects of astigmatism on vision and visual development provide strong indications for reliable means to correct astigmatic refractive errors. The following sections will provide an overview of the current clinically available methods of astigmatism correction, and potential future advances in these refractive correction options.

Short term physiological changes in astigmatism

There are a wide range of devices currently available for clinically assessing ocular and corneal astigmatism. The majority of studies indicate the accuracy and precision of these devices is sufficient for most clinical applications. However, the clinical assessment of astigmatism relies on the assumption that the eye's optics remain relatively static. In reality, a range of factors result in small physiological changes in the eye's optical properties of varying time courses and magnitudes, that have the potential to impact upon the clinical measurement of astigmatism, and hence the accuracy of the clinical astigmatic correction.

Changes in astigmatism with different visual tasks

Whether or not corneal astigmatism changes with accommodation has been the topic of a large number of studies, with some conflicting results as to whether ciliary muscle contraction results in corneal changes.[164-167] However, most recent studies examining changes in (anterior and posterior) corneal topography with accommodation indicate that the cornea remains stable during accommodation,[168-170] with any small variations in corneal astigmatism being attributed to cyclotorsional eye movements rather than a true change in corneal curvature (i.e. when small cyclotorsional ocular movements accompanying accommodation are accounted for, the change in corneal parameters is clinically and statistically insignificant).

Several studies have reported a small transient increase in ocular WTR astigmatism during accommodation (ranging from 0.02 to 0.40 DC per dioptre of accommodation) in young adults with a range of refractive errors,[171-173] while Mutti et al[174] found no significant change in astigmatism during accommodation up to ~4.5 D, in a cohort of emmetropic children. Radhakrishnan and Charman[173] speculated that such changes may be a result of an increase in crystalline lens tilt about the horizontal axis under the influence of gravity due to reduced zonular tension during accommodation. However, there is evidence to suggest that the lens remains relatively stable during accommodation and with changes in gravitational forces.[175] A number of theories have been proposed to explain the change in ocular astigmatism associated with accommodation including; sectorial structural differences in the ciliary body, crystalline lens or zonules, and regional or meridional differences in crystalline lens elasticity or ciliary muscle contraction.[176-177]

A number of recent investigations have also shown that brief periods of near work performed in downward gaze can result in small but significant short-term regional changes in corneal optics, which appear to be related to eyelid forces exerted on the cornea as a result of the narrower palpebral aperture during downward gaze.[85,86,178-180] The typical corneal changes observed following nearwork in downward gaze include a horizontal band of distortion in the superior cornea, often accompanied by an increase in ATR corneal astigmatism[85,178] (Figure 5). Potentially clinically significant changes in corneal astigmatism (> 0.125 D) have been observed following as little as 15 minutes of reading[180] and may take up to two hours to completely regress.[179] These alterations in corneal optics associated with eyelid pressure are thought to be limited to the superficial layers of the cornea (epithelial cell redistribution).

Given the location of the rectus muscle insertion points relative to the limbus, it is possible that extraocular muscle forces (such as those associated with convergence) have the potential to lead to changes in corneal shape. However, initial studies of central corneal changes associated with convergence were equivocal.[165,166] Recently, Read et al[182] observed statistically significant changes in superior corneal topography (a small increase in ATR astigmatism and an increase in vertical coma) following a short period of sustained convergence induced through prismatic spectacle wear during distance fixation. However, these small changes in astigmatism were attributed to the change in eyelid position (relative to the cornea) associated with convergence (i.e. a nasal movement of the cornea resulted in a relative narrowing of the palpebral aperture).

Diurnal changes in astigmatism

While it is well established that the cornea exhibits significant diurnal variation in both thickness and curvature,[183,184] undergoing a small amount of steepening (~0.25 D) throughout the day, more recent studies have specifically investigated the diurnal changes in both corneal and total ocular astigmatism. Read et al[185] used videokeratoscopy to examine the diurnal fluctuations in corneal astigmatism. A small reduction in corneal power vector J0 (astigmatism at 90/180°) was observed throughout the day (an increase in ATR astigmatism of around 0.02 D for a 5.5 mm pupil) along with a small, but statistically significant reduction in the J45 power vector (astigmatism at 45°/135°). Chakraborty et al[186] in a study of thirty young adults observed only small changes in horizontal/vertical and oblique ocular astigmatic power vectors, suggesting only slight fluctuations in ocular astigmatism throughout the day (mean amplitude of change: J0 = 0.11 ± 0.04 D and J45 = 0.08 ± 0.05 D, which equates to ~0.25 D amplitude of cylinder variability over the course of the day).

Tear film

Dynamic changes in the tear film following a blink can also result in subtle changes in the eye's optics. A number of studies have used high speed videokeratoscopy or wavefront sensors to investigate the fluctuations in corneal or total higher-order aberrations during natural blinking. Zhu et al[187] reported that the coefficients of astigmatic Zernike terms may vary significantly during the inter-blink period; secondary astigmatism at 45° increased, while secondary astigmatism at 0° decreased. Disruptions in the tear film (local areas of tear breakup or irregularity) may also result in significant increases in coma and spherical aberration.[188] Therefore, blinking, along with the quality, quantity and distribution of the tear film, may also slightly influence the clinical assessment of astigmatism.

Potential impact of physiological variations on clinical measures of astigmatism

Corneal and ocular astigmatism are subject to short term fluctuations dependent upon a number of factors, including; diurnal variation and physiological changes associated with reading or near work such as eyelid forces (or accommodation in the case of ocular astigmatism). While the magnitude of these changes in astigmatism are typically small, they are important to consider for research or clinical applications (e.g. refraction or refractive surgery) requiring a high degree of accuracy. Cessation of near work for at least 30 minutes prior to refractive assessment and corneal imaging in the presence of a stable tear film will

help to minimise the influence of short-term fluctuations in astigmatism during clinical measurements and thereby provide a more accurate clinical assessment of the astigmatism.

Spectacle lens correction of astigmatism

Spectacle lenses are the most commonly used clinical method for the correction of astigmatic refractive errors. Since spectacle lenses remain in a fixed position in front of the eye, they are typically not prone to lens rotation which can affect other correction options (e.g. contact lens corrections, toric IOLs) and can hence provide stable correction for a wide range of astigmatic refractive errors. However, since spectacle lenses are mounted at a distance from the eye, they can result in distortions of visual space, primarily due to meridional variations in image magnification that can occur with astigmatic spectacle lenses. These distortions are most prominent when viewing binocularly, increase with higher magnitude astigmatic corrections and with increasing vertex distance, and tend to be more obvious for oblique astigmatic axes.[189] The presence of these optical distortions with astigmatic spectacle lenses, although reduced with aspheric lens designs,[190] does mean that a period of adaptation is often required for newly prescribed astigmatic spectacles, particularly for high prescriptions.

Although failure to adapt to prescribed spectacles is uncommon (estimated rate of 1-3%),[191] difficulties in adapting to astigmatic spectacle corrections are one of the more common reasons for intolerance to spectacle corrections in optometric practice. In a large retrospective study of 25,718 spectacle prescriptions from a university optometric clinic over a 6 year period, astigmatic prescriptions accounted for more than 60% of the 39 patients dissatisfied with their spectacles due to an “inability to adapt to an accurate refractive correction”.[192] The potential problems with adaptation to astigmatic spectacle corrections means there are a number of documented “prescribing rules” to assist in patients adapting to new astigmatic spectacles.[191] These strategies to reduce spatial distortions with newly prescribed astigmatic spectacles typically involve partial prescription of the cylinder power (while maintaining the optimum spherical equivalent), or rotation of the cylinder axis towards 180 or 90 (or towards the habitual cylinder axis).[189] A survey of clinical optometrists suggests that a large proportion of practitioners (more commonly those with greater clinical experience) do tend to follow these “prescribing rules” (or variations of these rules) in making their clinical spectacle prescribing decisions for patients with astigmatism, particularly for changes in cylinder power.[193]

In addition to these empirical “rules of thumb” to assist in spectacle adaptation, there are also a number of published guidelines for the correction of astigmatism in paediatric populations.[194-196] The evidence that uncorrected astigmatism in early childhood is associated with the development of amblyopia means that the correction of significant astigmatism in paediatric subjects can be critical for normal visual development. However, the correction of astigmatism in childhood is complicated by the fact that the prevalence of moderate levels of astigmatism is common in early infancy, and there is a tendency for astigmatism in infancy to reduce substantially over time. The majority of the currently published guidelines (Table 1) have similar suggested thresholds for the prescribing of spectacles for astigmatism in early childhood, with the ‘cut-off’ thresholds being higher for younger infants (0-2 years) compared to older infants (> 2 years), consistent with the normal emmetropisation of astigmatic refractive errors. Some authors[194,195] also recommend partial prescription of astigmatic refractive errors in younger children (< 2 years), to try and reduce the impact of the correction upon the normal emmetropization process. It should be noted that these ‘rules’ are suggested to be used as a general guide only, and prescribing decisions are likely to vary dependant on the individual child (for example, Leat[195] recommends a lower threshold for prescribing in cases of oblique astigmatism since oblique astigmatism greater than 1.00 D is rare in children older than 12 months and is more strongly associated with the development of amblyopia). The prescription of spectacles for older children and adults is generally based upon a range of clinical factors such as the magnitude of astigmatism, the level of uncorrected visual acuity, the specific visual demands of the individual and the presence of symptoms. However, the fact that relatively small magnitudes of astigmatism can result in noticeable decrements in vision[96] and in increases in reported symptoms,[122,123] suggests that certain patients (e.g. those with high visual demands) may benefit from the correction of even relatively small magnitudes of astigmatism (e.g. ≥ 0.75 DC).

Although the majority of current spectacle lenses provide a correction of only the sphero-cylindrical refractive error to the nearest 0.25 D, advances in ocular measurement methods (e.g. wavefront aberrometry) and spectacle lens manufacturing technology, means that the eye’s optical quality can now be defined and potentially corrected more precisely and comprehensively. This provides the potential to correct both lower-order (i.e. the traditional sphero-cylinder), and higher-order optical aberrations (e.g. second-order astigmatism). However, the correction of higher-order aberrations with spectacle lenses presents a number of challenges, since fixation away from the centre of the lens will result in the introduction of substantial levels of residual aberrations. Recently, Carl Zeiss Vision (Aalen, Germany)

introduced spectacle lenses ("i.Scription" ® lenses) that utilize both the subjective refraction result and wavefront aberrometry using a proprietary method to derive a customised spectacle prescription, however there are currently no peer-reviewed reports on the efficacy of these lenses compared to standard spectacle corrections. Developments in spectacle lens materials such as liquid crystal lenses[197] or gradient index materials,[198] have the potential to improve spectacle correction of astigmatism in the future, by allowing the manufacture of more complex optical designs (e.g. to reduce optical distortions associated with high levels of astigmatism, or to correct higher-order optical aberrations) or to even potentially provide dynamic corrections to optimise optical quality for different visual tasks.

Contact Lens Correction of Astigmatism

Since contact lenses fit directly on the eye, their effects on image magnification are minimal, which means the correction of astigmatism with contact lenses does not result in the same spatial distortions that can occur with astigmatic spectacle corrections. However, the requirement for an accurate alignment of the axis of the toric contact lens with the total astigmatic error of the eye creates a challenge for some forms of contact lens correction that does not exist to the same extent with spectacle correction. Misalignment between the toric contact lens and the ocular astigmatism can result in substantial residual astigmatism (Figure 6). Soft toric contact lenses typically utilize the forces generated by the eyelids during blinking to align the lens to the appropriate axis. This is a difficult balance of biomechanical forces and lens stability. Spherical rigid contact lenses and hybrid lenses with a rigid core rely on the tear fluid lens generated between the back surface of the lens and the anterior corneal surface to correct most of the anterior corneal astigmatism. However, toric rigid lenses are required when this optical approach is not appropriate. Orthokeratology to correct astigmatism is still in its infancy, but early evidence examining this contact lens modality appears promising (at least for low levels of astigmatism).

Rigid contact lenses

One of the useful optical outcomes of spherical rigid contact lenses is that the tear fluid lens that forms between the lens and cornea has a shape at the corneal surface which is identical to the cornea (i.e. the steeper/flatter corneal meridian is matched by the steeper/flatter tear lens meridian). Since the refractive index of the tears (n = 1.336) is close to that of the cornea (n = 1.376), this means that at the tear to cornea interface, the refractive power at

this surface is reduced by about 89% compared to that in air, and the amount of astigmatism at this surface is also reduced. Therefore, an anterior corneal surface with principal meridian radii of 7.5 and 7.8 mm has about 1.93 D of paraxial refractive astigmatism, whereas the same corneal surface beneath a rigid lens has a refractive astigmatism of about 0.21 D (89% lower). A similar optical advantage accrues beneath a hybrid rigid lens with a soft skirt. This optical principle of spherical rigid contact lenses allows the successful "masking" of most anterior corneal astigmatism, and extends to all optical imperfections arising from the shape of the anterior corneal surface. The correction of keratoconus with spherical rigid contact lenses relies on this same principle, where the tear fluid lens also masks most of the irregular corneal refractive power (i.e. higher-order aberrations such as coma) induced by the condition.[199]

However, the approach of using rigid lenses with a spherical back surface to mask anterior corneal astigmatism is limited when certain conditions arise, such as when the internal astigmatism has a large magnitude or different axis compared to the anterior cornea.[200] In this circumstance, a rigid bitoric lens (i.e. a rigid lens with toric front and back surfaces) is typically required. A related problem arises when the magnitude of anterior corneal astigmatism is greater than about 2 D, since in these cases the spherical back surface of the lens no longer provides an adequate fit to the cornea.[200] Again, this requires a bitoric rigid lens design to provide a suitable fit to the cornea and an appropriate optical correction of the astigmatism. The toric back surface of the lens is typically designed to closely align with the principal meridians of the central anterior cornea, in this way the lens back surface provides a "hand-in-glove" alignment fitting that allows the lens to "self align" with the anterior corneal astigmatism.

A rigid lens can also flex or bend on an astigmatic cornea, inducing unwanted residual astigmatism. The flexure of spherical rigid contact lenses on toric corneas has been shown to be influenced by factors such as the lens fit (steep versus flat),[201,202] the magnitude of corneal astigmatism,[203,204] the lens material modulus,[204,205] back optic zone diameter[206] and the lens thickness and power.[203-205] This flexure can be visualized and quantified by performing videokeratoscopy or keratometry over the lens on the eye.

The use of orthokeratology reverse geometry rigid contact lenses to flatten the central cornea is now a well-established method for the temporary, reversible correction of myopic refractive errors.[207] The correction of corneal astigmatism with orthokeratology is more complex, but a number of recent studies are now reporting controlled reductions in corneal astigmatism of about 1.5 D (Figure 7).[208,209]

Soft contact lenses

Unlike rigid contact lenses, current soft lenses wrap almost completely to the underlying cornea and therefore create a tear fluid lens that has minimal/negligible optical power. Measurements of the masking of astigmatism with spherical soft contact lenses show little difference in the toricity of the front surface of the lens from that of the underlying cornea,[210,211] or masking of refractive astigmatism.[212] As noted by McCarey et al,[213] since the lens has a higher refractive index than the cornea, the amount of refractive astigmatism may also slightly increase if the lens wraps completely to the cornea. Attempts to mask anterior corneal astigmatism with thicker soft spherical lenses have not been particularly effective.[199,214] Similarly, the use of aspheric soft lenses that reduce the spherical aberration of the eye have shown no significant improvement in visual acuity with low levels of astigmatism.[236] It is generally agreed that the correction of astigmatism of 0.75 D or greater is worthwhile with soft toric contact lenses.[216-218]

The correction of astigmatism with soft contact lenses is normally undertaken with soft toric lenses that correct the total astigmatism of the eye. The optical zone of the lens may have the toric surface on the front, the back surface, or split between both surfaces. Since the lens wraps to the underlying cornea, the optical outcome is almost identical in these three scenarios, but the mechanical wrapping forces (strain) generated within the lens do differ between these design approaches. To maintain the axis of the astigmatic correction of the soft toric contact lens at the appropriate orientation, the lens typically contains “stabilization zones”. These regions of the lens are designed to harness the force of the upper eyelid during blinking to orientate the lens at a consistent location. Spontaneous blinking normally occurs at a rate of about 14.5 ± 3.3 blinks per minute in primary gaze[219] and while the upper eyelid sweeps down and slightly inward, the lower eyelid makes a small predominantly horizontal nasal movement (Figure 8). By incorporating a vertical thickness differential in soft toric lens designs (in the haptic/peripheral region outside the central optical zone), the upper eyelid can “squeeze” against the thicker regions of the lens during a blink and rotate the lens

to a consistent location. This squeezing force of the eyelid on the lens was termed the "watermelon seed principle" by Hanks,[220] who provided anecdotal evidence that gravity played little role in lens stabilization. A number of lens and ocular factors can influence the lens' location and rotational stability including post-blink movement and lens tightness, and aspects related to lid morphology.[221]

The quality of the optical correction of astigmatism with soft toric lenses is sometimes slightly inferior to that with spectacles because of various factors. After insertion, soft toric lenses typically require at least a few blinks to align themselves at the correct orientation in the eye and then show a small degree of rotational instability with each blink that can manifest as fluctuations in visual quality.[222,223] The majority of disposable soft toric contact lens types that are available in the marketplace are also limited in terms of cylinder power (e.g. often covering 0.75 to 2.25 D cylinders) and axes (e.g. 90° and 180° ± 10°, 20° and 30°). The resulting compromise in cylinder power and/or axis can also reduce visual performance. However, custom soft toric lenses (any cylinder power or axis) are available from a wide variety of manufacturers.

A large number of different contact lens correction options are currently available for the astigmatic patient. However, developments in ocular measurement and lens manufacturing technology leave open the possibility for more advanced contact lens corrections in the future. Custom contact lens corrections to correct higher-order aberrations have been developed for patients with high levels of ocular aberrations (e.g. those with keratoconus).[224,225] Compared to spectacle lenses, the correction of higher-order aberrations with contact lenses has the advantage that the correction moves with the eye, (which limits the increases in aberrations with eye movements inherent with spectacle corrections) however reducing the influence of lens rotation and decentration remains a challenge. Continued developments in this area provide the potential for more precise and comprehensive custom contact lens corrections in the future (that correct both lower-order and higher-order optical aberrations) that have the potential to provide enhanced visual correction of astigmatic refractive errors.

Surgical Correction of Astigmatism

There are a range of different surgical treatments that are currently available for the correction of astigmatism. Similar to contact lens corrections, since surgical treatments are applied at the corneal or IOL plane, the minimal vertex distance between the correction and the eye means that meridional magnification (and hence distortions of spatial vision) is generally not an issue for surgical corrections of astigmatism. However, accurate alignment between the surgical correction and the eye's optics, and the rotational stability of the correction are critical for the reliable surgical correction of astigmatism.

Cataract surgery

As corneal incisions are required to perform cataract surgery, the procedure itself can alter the pre-surgical level of corneal astigmatism, since peripheral corneal incisions result in a flattening of the cornea along the meridian of the incision. The size of corneal incisions influences the amount of induced astigmatism, with larger incision widths typically causing larger changes in astigmatism.[226,227] Peripheral corneal incisions of 3.0 to 3.2 mm in width typically lead to approximately 0.50 D change in corneal astigmatism,[228] with larger width 5.0 mm incisions resulting in up to 1.0 D of corneal astigmatism change.[226,227] As modern surgical techniques have evolved, the use of smaller incisions has become possible (so-called micro-incision cataract surgery). Although micro-incision cataract surgery with incision sizes of ~2.0 mm, has been shown to reduce the magnitude of surgically induced corneal astigmatism compared to ~3.0 mm width clear corneal incisions,[229,230] the magnitude of surgically induced corneal astigmatism can still be ~0.50 D in some cases.[229] Changes in astigmatism as a result of corneal incisions during cataract surgery can be taken advantage of by the surgeon, to reduce post-operative astigmatism by placing the incision along the steep corneal axis. This approach for astigmatism reduction during cataract surgery is recommended for patients with ≤ 1 D of corneal astigmatism.[231] For astigmatism greater than 1 D, additional incision/s placed in the peripheral cornea at the time of surgery (e.g. "opposite clear corneal incisions" where the phacoemulsification incision is made along the steep axis and an additional incision is made on the opposite side of the cornea,[232] or "limbal relaxing incisions" where the phacoemulsification incision is made in a standard position and additional incisions in the peripheral cornea are made along the steep corneal axis[233]) can result in larger magnitudes of surgically induced astigmatism (typically up to 1.5 D to 2.0 D). A number of nomograms are published to tailor the location and size of peripheral corneal incisions to the intended magnitude of astigmatism correction.[231] The use of corneal

relaxing incisions for the correction of astigmatism during cataract surgery relies on accurate prediction of the corneal response to the incision, which depends upon a variety of factors including the predictability of the individual corneal healing response and corneal biomechanical properties.

Another option for the correction of astigmatism during cataract surgery is the use of toric IOLs, which were first introduced in the early 1990s.[234] Toric IOLs are now commonly used in patients undergoing cataract surgery who have > 1.0 D of corneal astigmatism.[231,235] A wide variety of toric IOLs are currently available in a range of designs, materials and cylindrical powers (see Visser et al[235] for an in-depth review of current designs). The optimal correction of astigmatism with toric IOLs depends upon two main factors: the alignment of the IOL at the time of surgery, and the rotational stability of the lens once implanted. Axis alignment at the time of surgery is commonly achieved using a manual process involving the marking of the limbus with respect to the horizontal (typically performed with the patient sitting at the slit lamp prior to surgery), and then aligning the intended axis with respect to this marker.[236] Although this process accounts for potential cyclotorsional eye movements occurring as a result of supine posture during surgery, it has been reported that this manual marking procedure results in a mean error in IOL placement of approximately 5°.[236] Newer developments designed to more precisely align the IOL axis at the time of surgery, such as iris feature detection[237] and tracking,[236] and intraoperative wavefront measurements[238] have the potential to reduce misalignments and improve refractive outcomes. Since fusion of the IOL with the capsular bag following lens implantation is thought to prevent lens rotation post-surgery, factors that can influence the interaction between the IOL and the capsular bag, such as IOL material,[239] IOL diameter[240] and haptic design[241] are all thought to play a role in the rotational stability of the IOL post-insertion.

Although early studies from the first generation toric IOLs indicated significant lens rotation (of > 10°), and hence axis misalignment in 20-30% of patients,[242,243] more recent reports indicate only small magnitudes of axis misalignment (typically less than 10% of patients with more than 10° misalignment) with modern toric IOL designs.[244-247] A large number of studies have evaluated the refractive outcomes from a range of different toric IOLs, with most recent studies reporting good results in the majority of patients with low to moderate levels of astigmatism (typically between 1.00 to 2.50 DC).[244,245,248,249] These studies have reported the percentage of patients with post-operative residual astigmatism of 0.50 DC or less ranging from 53-92% and with 1.00 DC or less ranging from 80-100%.

A relatively recent development in the correction of astigmatism during cataract surgery is the light adjustable IOL.[250] This IOL is made of a material containing light sensitive silicone that allows the refractive power of the lens to be altered post-operatively through exposure of the lens to precisely controlled ultraviolet light. The use of these lenses allows the adjustment of both spherical and astigmatic powers to be made following surgery. Since these adjustments in refractive power are made after lens implantation, and following a period of post-surgical refractive stabilization (typically around 2 weeks), these IOLs provide the potential for more precise astigmatic corrections, since any surgically induced astigmatism can be accounted for reliably, and because the fusion between IOL and capsular bag is likely to have occurred by the time the final refractive correction is applied, rotational instability is also limited. Recent studies suggest promising results with these lenses for the correction of up to 2.00 D of astigmatism, with residual astigmatism of less than 0.50 DC in all patients.[251,252] It should be noted though that the studies to date published with these lenses for patients with astigmatism have only included small numbers of patients (n = 5-10), with relatively short-term follow up (up to 12 months), so further research is required to determine the long term efficacy of these lenses in larger numbers of patients. Another recent development in cataract surgery is the use of femtosecond lasers to assist in performing aspects of the surgical procedure. Femtosecond lasers can make very precise corneal incisions (in terms of incision angle, position, size and depth),[253-257] and have also been shown to produce more uniformly sized, shaped and positioned capsulotomies.[258,259] These factors would be expected to result in improved IOL centration and stability and more predictable surgically induced astigmatism, which suggests that the continued refinement of femtosecond laser assisted cataract surgery methods, is likely to result in improved refractive outcomes for astigmatic patients undergoing cataract surgery.

Although moderate levels of astigmatism can be reliably corrected during cataract surgery, the correction of high levels of corneal astigmatism (> 3.0 D) remains challenging. A number of different approaches have been used for the correction of high levels of corneal astigmatism during cataract surgery, including combining toric IOLs with limbal relaxing incisions,[260,261] and the use of piggyback toric IOLs.[262] More recently, the use of high powered toric IOLs has also become an option for patients with high levels of corneal astigmatism.[263,264] Refractive outcomes from studies examining high powered toric IOLs have generally been positive, although they have typically demonstrated higher levels of postoperative residual astigmatism (e.g. Hoffman et al[263] reported postoperative astigmatism of greater than 0.50 D in more than 50% of their patients with more than 2.50 D of preoperative astigmatism) than studies examining the correction of lower levels of

astigmatism with toric IOLs. This is not unexpected, since small misalignments of high powered toric lenses can result in significant residual astigmatism (Figure 6).

Another potential surgical option for the correction of astigmatism in patients without cataract is the implantation of a phakic IOL. Since these lenses are inserted in the anterior or posterior chamber, in front of the patients existing crystalline lens, the natural accommodative ability is retained. Phakic IOLs are typically used as an alternative to corneal laser refractive surgery for young adult patients with very high refractive errors, and toric lenses are available. Studies examining the correction of astigmatism with toric phakic IOLs have generally shown good alignment and rotational stability of the lenses (with less than 10% of patients exhibiting more than 10° of axis misalignment), with average residual cylindrical refractive errors ranging from 0.50 DC to 1.50 DC.[265-268] Studies comparing phakic IOL implantation with corneal laser refractive surgery for the correction of high myopic astigmatism have reported similar efficacy for the correction of astigmatism between the two refractive procedures, although significantly better distance visual acuity has been reported for phakic IOL implantation compared to the corneal refractive surgery, which may be related to changes in ocular higher-order aberrations associated with the corneal refractive surgery.[269-271]

Corneal refractive surgery

The other major surgical option for the correction of astigmatism is corneal refractive surgery. These procedures reshape the corneal surface in order to correct refractive error (including astigmatism), most commonly through laser ablation of corneal tissue. An array of different corneal surgical techniques have been developed and refined over a number of years for the correction of astigmatism, with lamellar procedures such as laser-in-situ keratomileusis (LASIK) and surface ablation procedures such as photorefractive keratectomy (PRK) being the most commonly performed corneal refractive procedures. Similar to other refractive corrections, the key to effective correction of astigmatism with corneal refractive surgery is accurate alignment of the corneal treatment with the ocular axis of astigmatism. Most modern laser refractive surgery systems use eye tracking in order to maintain accurate alignment of the ablation during the procedure and iris registration can also be used to reduce potential misalignments due to cyclotorsional eye movements during surgery. There is some evidence that the use of iris registration may improve refractive outcomes in some cases.[272,273] Numerous studies have examined the efficacy of laser

refractive surgery procedures, and results with modern LASIK and PRK platforms generally demonstrate predictable correction of low to moderate astigmatic refractive errors (up to ~3 DC), particularly for myopic astigmatism,[274] with recent studies reporting average post-surgical levels of residual refractive astigmatism from 0.11 DC to 0.68 DC.[275-280] Although refractive stabilisation and visual recovery is generally faster with LASIK compared to PRK, studies comparing the two procedures have generally found the refractive and visual outcomes in the long term to be similar for the two procedures using modern techniques for patients with low to moderate myopic astigmatism.[274]

It is well established that although conventional corneal refractive surgery procedures effectively correct sphero-cylindrical refractive errors, they can result in an increase in the eye's higher-order aberrations, particularly spherical aberration.[281] In recent years, wavefront-guided refractive surgery procedures (including LASIK and PRK) have been developed that use a customized ablation pattern based upon ocular wavefront aberrometry and aim to reduce or eliminate the eye's higher-order aberrations, as well as the sphero-cylindrical refractive error.[282] The majority of reports on wavefront-guided LASIK suggest that small magnitude post-surgical increases in ocular aberrations still occur (compared to the pre-surgical level of aberrations), however the magnitude of increase in aberrations is generally less than found with traditional laser refractive surgery approaches.[282] There is also some evidence that the correction of sphero-cylindrical refractive errors is more precise using wavefront guided procedures.[282] The majority of current laser refractive surgery platforms base their ablation profile upon either wavefront-guided, or wavefront optimised (an approach that attempts to eliminate the surgically induced increase in spherical aberration, rather than reducing the patients pre-existing aberrations), or topography guided (where corneal topography data is used to customise the ablation profile) algorithms.

Although there is clear evidence that low to moderate levels of astigmatism (particularly myopic astigmatism) can be corrected effectively with modern corneal laser refractive surgery systems, the correction of high levels of astigmatism (> 3.0 D) and particularly hyperopic astigmatism remain a challenge for corneal laser refractive surgery. Recent studies examining patients with high astigmatism (> 3.0 D), indicate that the accuracy of astigmatism correction with laser refractive surgery for these patients is lower than that found for patients with lower levels of astigmatism, with mean reported levels of post-surgical astigmatism ranging from 0.45 DC to 1.29 DC.[283-286] A number of these studies have found mean post-surgical astigmatism levels of greater than 1.00 D, with evidence of under

correction of astigmatism.[283,285,286] The accuracy and precision of high astigmatic correction also appears to be lower in hyperopic[285] and mixed astigmatism[283] compared to myopic astigmatism.[284,285] Future improvements in eye tracking and iris registration to optimise the treatment alignment and centration, along with continued developments to improve ablation profiles for astigmatism may help to improve outcomes with laser refractive surgery for high astigmatism.

A recently developed corneal refractive surgery technique is the refractive lenticule extraction procedure. In this procedure a femtosecond laser is used to cut a lens shaped piece of intra-stromal corneal tissue in order to reshape the corneal surface (rather than ablating corneal tissue with an excimer laser as occurs in procedures such as LASIK and PRK).[287] The lenticule is then removed from the cornea through a flap or a small peripheral corneal incision (in the case of the "small incision lenticule extraction", or SMILE procedure). There is some evidence that this technique causes less change in corneal sensitivity and post-operative corneal staining in comparison to LASIK procedures,[288] and since the SMILE procedure uses only a small incision through which the intrastromal lenticule is removed, flap related complications that can occur with LASIK[289] are avoided. Preliminary refractive results suggest the procedure is effective in the correction of myopic astigmatism, with a recent study of 113 patients with preoperative astigmatism ranging from 0.25 to 6.00 D (mean 0.96 ± 0.87 D), reporting 80% of cases exhibiting 0.50 DC or less refractive astigmatism 6 months postoperatively.[290] Only a small number of prospective studies have evaluated this procedure for the correction of astigmatism, therefore further research is required examining the longer term effects and the effectiveness, particularly in cases of high astigmatism.

Conclusions

Astigmatism is one of the most common refractive errors encountered and managed in clinical ophthalmic practice. Uncorrected astigmatism results in a wide range of visual deficits and short and longer term visual adaptations. Even relatively small magnitudes of uncorrected astigmatism can influence visual performance, particularly for tasks with high acuity demands. The precise and reliable correction of astigmatism is therefore critical, particularly in children where uncorrected astigmatism can impact upon normal visual

development, and result in the development of amblyopia. A wide variety of refractive correction options are now available for the clinical management of astigmatism. Although the vast majority of patients are satisfied with the refractive correction of their astigmatic refractive errors, the continued development of reliable ocular measurements technologies, improvements in spectacle and contact lens materials, designs and manufacturing, and the advancement of various refractive surgery technologies promises more precise, comprehensive and stable correction of astigmatism in the future.

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FIGURES:

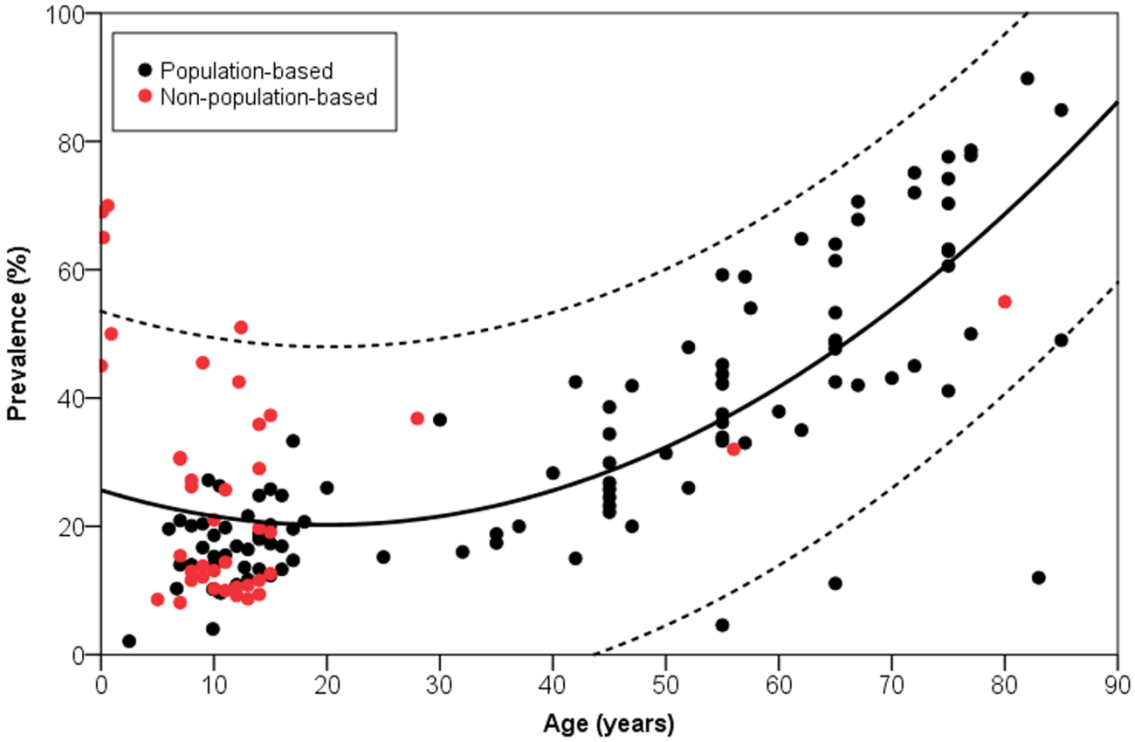

Figure 1: Changes in the prevalence of astigmatic refractive errors > 0.50 D with age. Data derived from a range of studies of age related changes in astigmatism (both population based and non-population based).[5-43] Solid line = best fit, dashed lines = 95% confidence intervals.

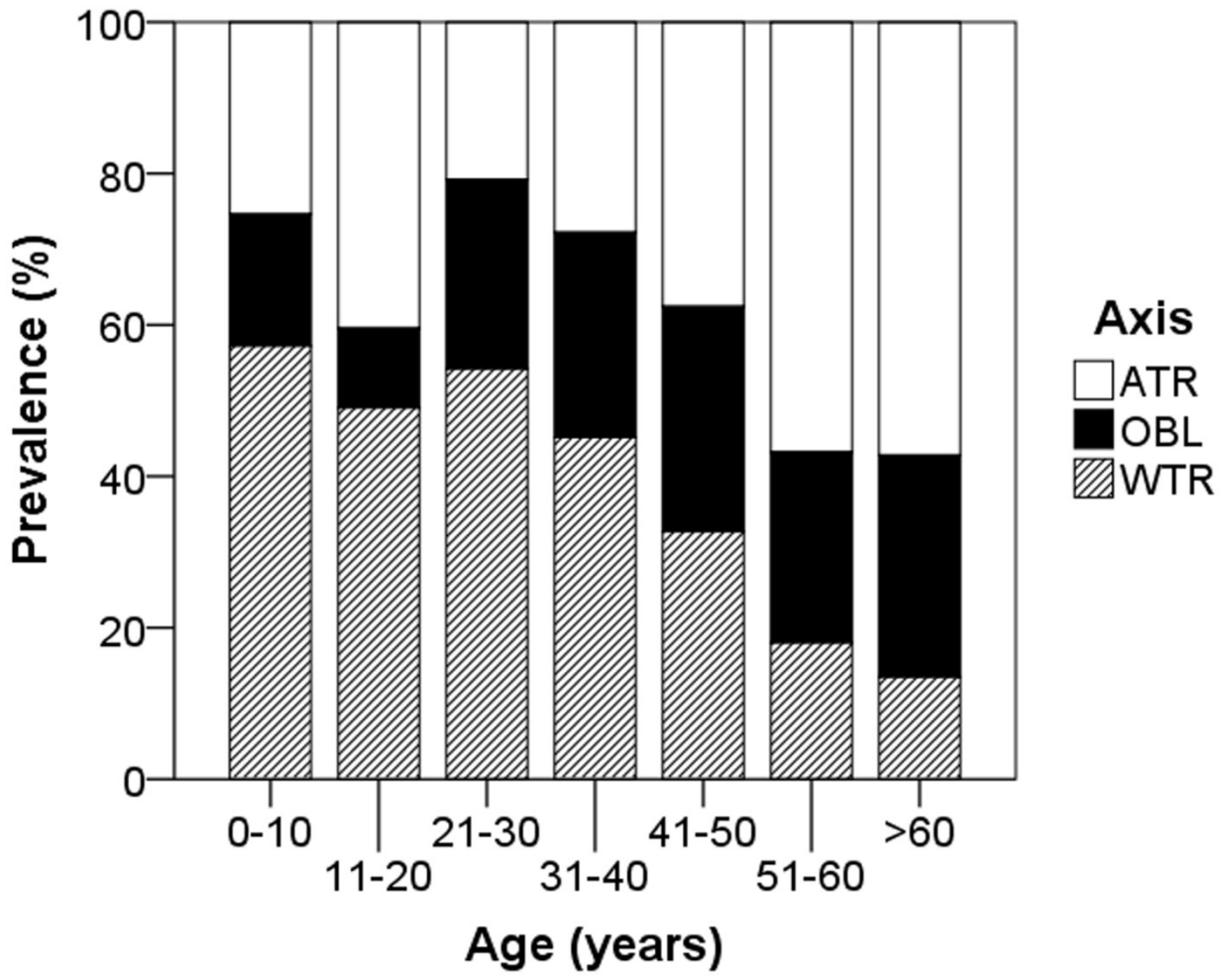

Figure 2: Changes in the prevalence of different astigmatic axes with age based upon a range of population studies. [24,29,33,39,42-44,48,51-55]

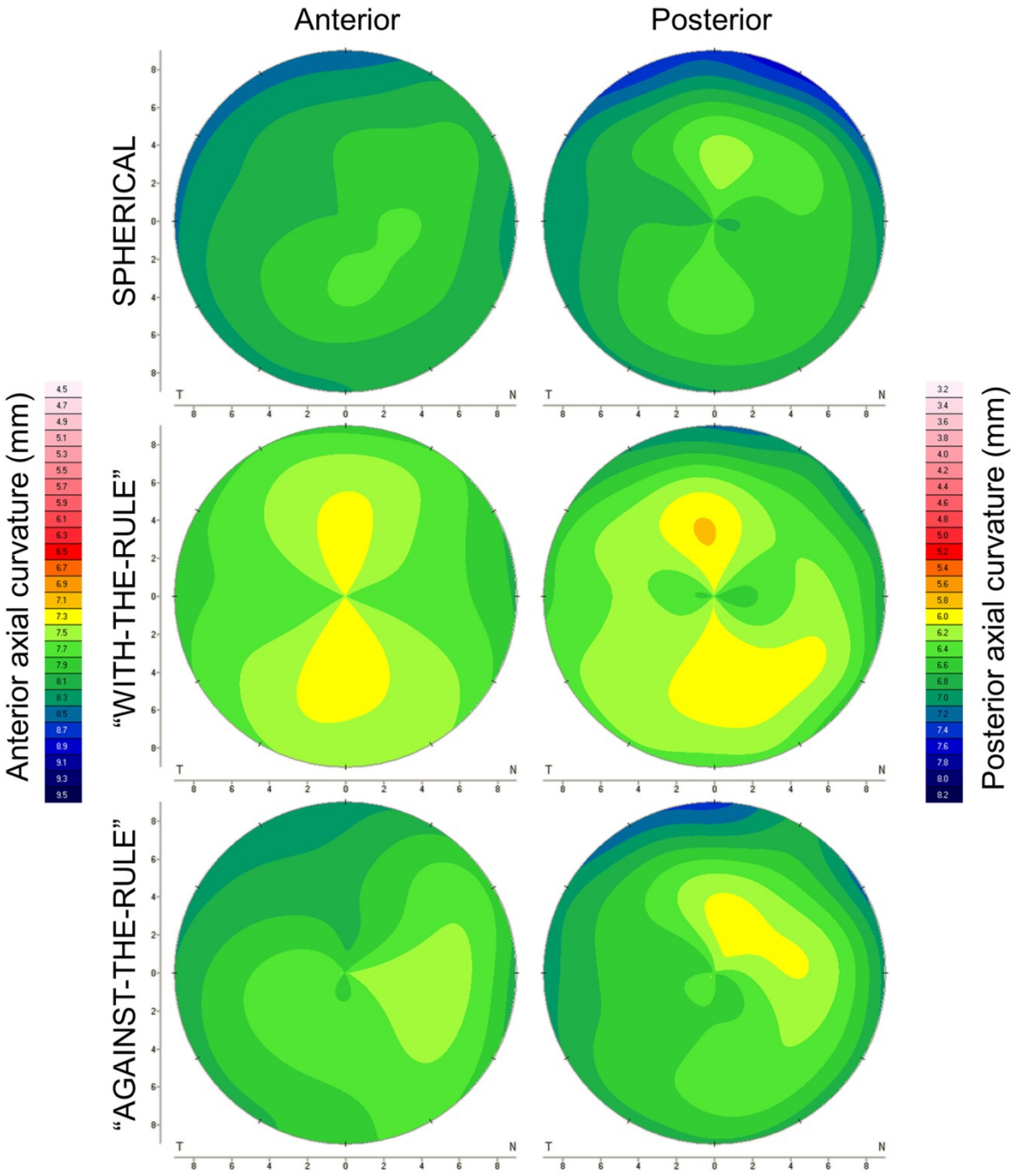

Figure 3: Examples of the pattern of anterior and posterior corneal astigmatism (derived from measurements with a rotating Scheimpflug camera) in three example patients exhibiting a spherical anterior cornea (top), a with-the-rule astigmatic anterior cornea (middle) and an against-the-rule astigmatic anterior cornea (bottom). Note that although the orientation of the anterior corneal astigmatism differs substantially amongst the 3 cases, the posterior corneal curvature consistently has the steepest meridian oriented close to the vertical meridian (which effectively results in an ATR astigmatic contribution from the posterior cornea to the total corneal astigmatism).

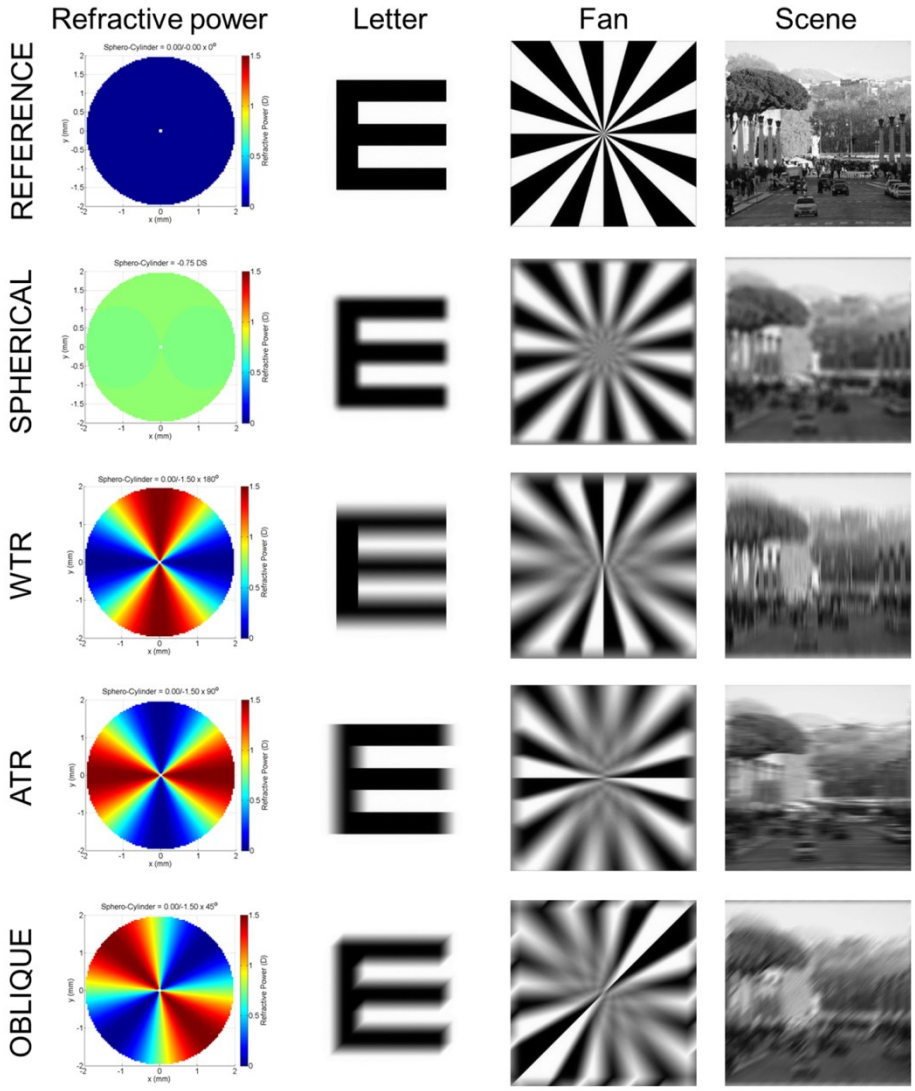

Figure 4: Simulation of the influence of spherical refractive error (-0.75 DS) and with-the-rule (WTR), against-the-rule (ATR) and oblique astigmatic refractive errors (-1.50 DC) upon vision of a letter, a fan chart and a typical street scene.

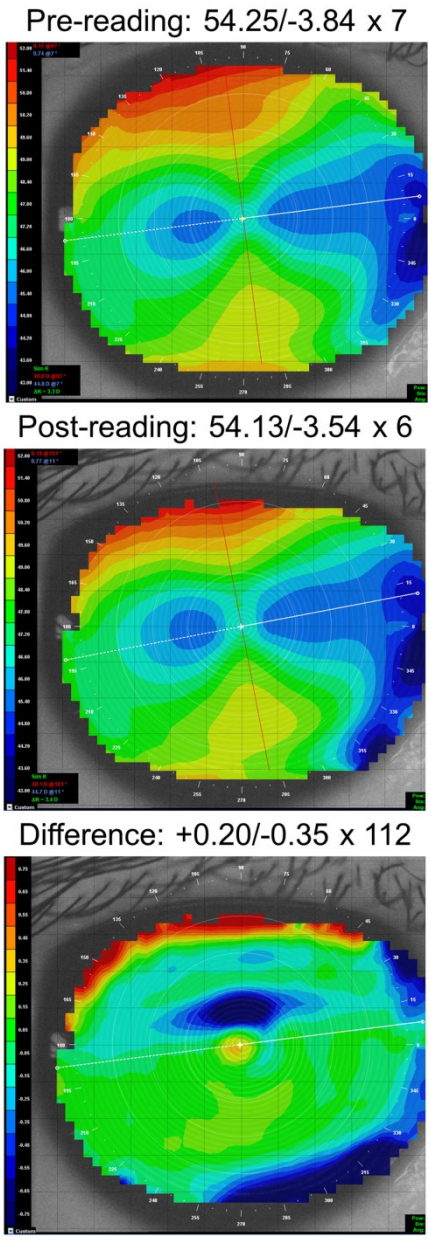

Figure 5: Example of changes in corneal topography in a patient following a 15 minute reading task in downward gaze. Corneal refractive power maps from before (top) and after the reading task (middle), along with the difference between the two conditions (bottom) are shown. Note the ATR shift in corneal astigmatism (corneal sphero-cylindircal power (D) derived from the corneal refractive power data, assuming a corneal refractive index of 1.376, over a 6 mm diameter) of approximately 0.35 D following the task, and the horizontal band of topographical change corresponding to the position of the upper eyelid during downward gaze.

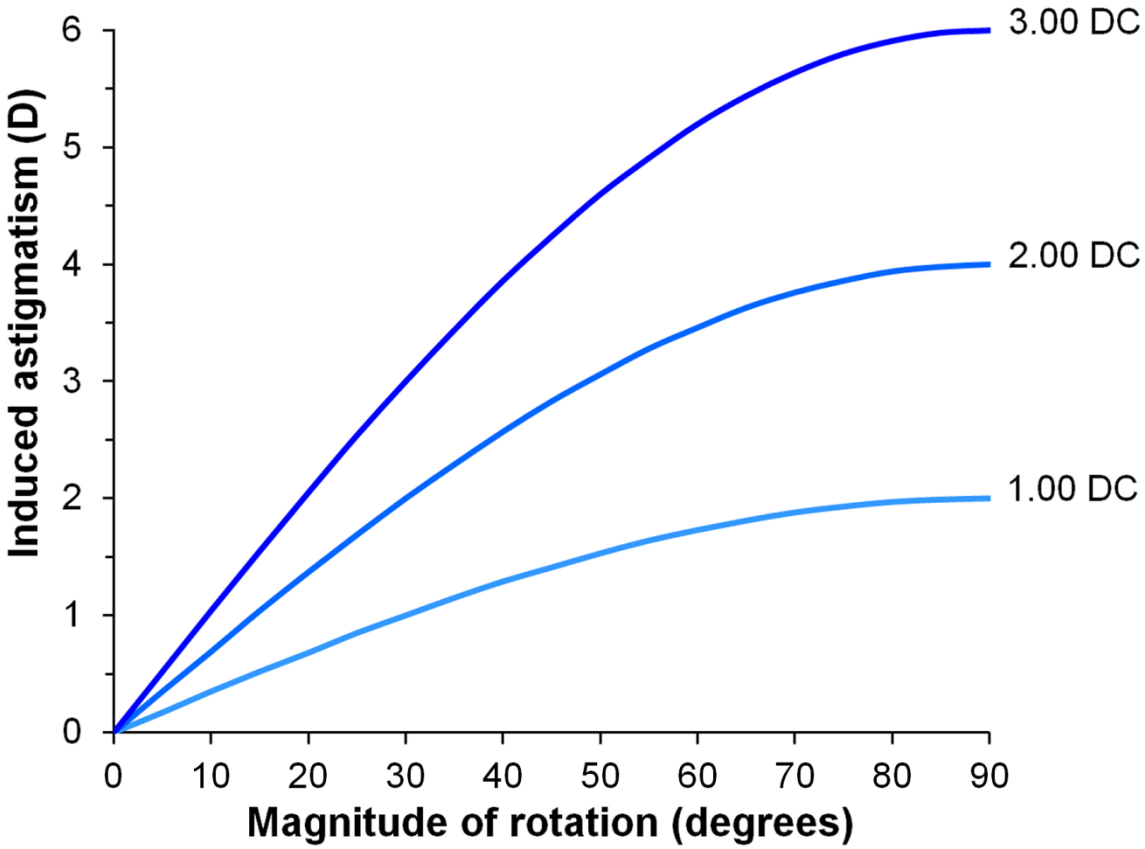

Figure 6: Illustration of the amount of astigmatism induced by rotation of 3 different astigmatic refractive corrections of different magnitudes (1.00 DC, 2.00 DC and 3.00 DC). Note that 30 degrees of rotation results in induced astigmatism of the same magnitude of the correcting lens.

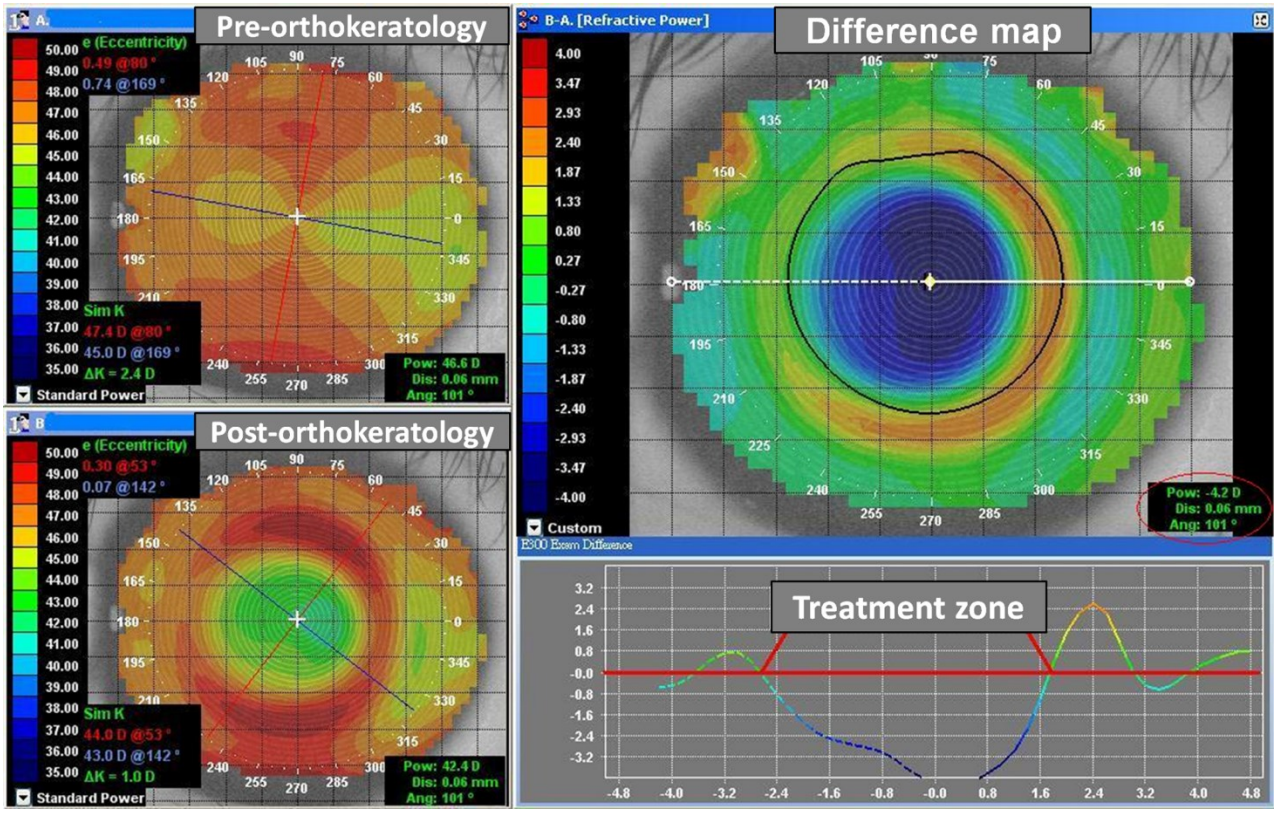

Figure 7: Example of orthokeratology correction of myopic astigmatism for a patient with 2.4 D of WTR corneal astigmatism, which reduces to 1.0 D after treatment. Pre- and post orthokeratology corneal refractive power maps are shown along with the difference, illustrating the change in corneal refractive power. Note the reduction in corneal astigmatism in the post-lens wear map and the overall reduction of myopia by 4.2 D. Image courtesy of Connie Chen, School of Optometry, The Hong Kong Polytechnic University.

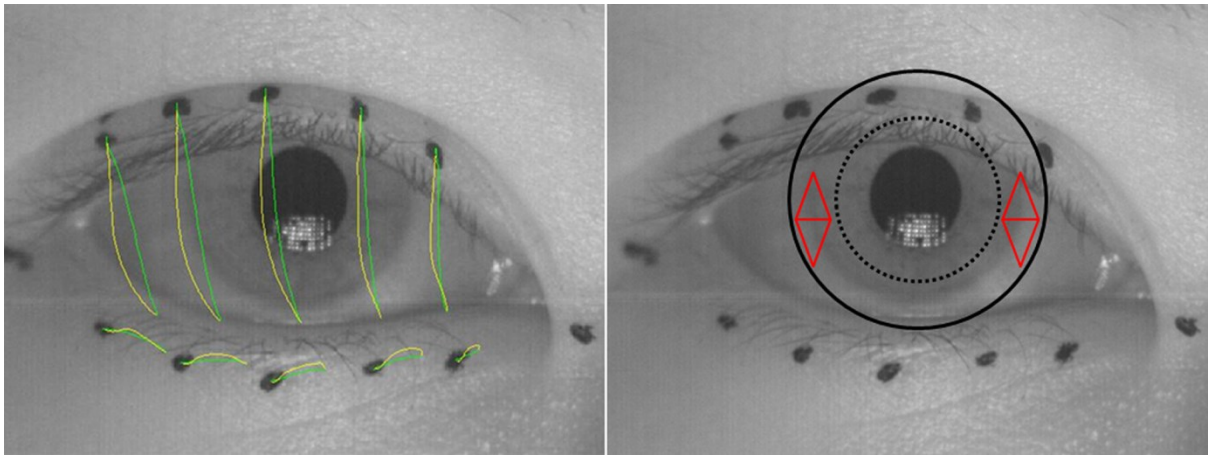

Figure 8: Illustration of the eyelid movements that occur with a typical complete blink. Green lines in the image represent the movement recorded (based upon high speed filming of a blink) of the markers on the eyelid during the downward phase of a blink and yellow lines from the upward phase (Left). Note the predominantly vertical and slight horizontal movements of the upper lid, and predominantly horizontal movement of the lower lid. A soft toric lens outline is also illustrated, with stabilizing zones in the periphery on the same eye (Right). Images courtesy of Sammy Phang and Robert Iskander.

Supporting information illustrates dynamic images of the blink.

Tables

Table 1: Overview of published guidelines for the correction of astigmatic refractive errors in infancy and early childhood

Authors	Age			
	0-1 years	1-2 years	2-3 years	4 years and older
Bobier[194]	> 2.00 D*		> 2.00 D	
Leat[195]	> 2.50 D*		≥ 2.00 D	≥ 1.50 D
AAO preferred practice pattern[196]	≥ 3.00 D	≥ 2.50 D	≥ 2.00 D	Not specified

* Indicates partial correction recommended (i.e. decrease cylinder power by half)